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Technical Support Package

Insect-Inspired Optical-Flow Navigation Sensors

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Technical Support Package

for

INSECT-INSPIRED OPTICAL-FLOW NAVIGATION SENSORS

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Implementation Of An On-Chip Insect-Inspired Optic Flow Based Navigation Sensor

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I. Introduction

Many animals such as insects rely primarily upon movement of features within their visual field, rather than upon stereo vision, for cues about their environment. This movement, termed “optic flow”, has been shown to be very effective as a means of obstacle avoidance and speed/altitude control in robotic navigation. Experiments to date have employed high-resolution panoramic imagery coupled to a separate optic flow engine to determine flow of many features in the scene. Traditionally, however, such systems have been computationally expensive, large, and complex, consisting of high-resolution imagers followed by a programmable computer. Such systems do not scale well for inclusion on miniature robotic platforms, on which power, mass, and volume are all at a premium.

Recent advances in optical navigation have made widely available “optical mouse” chips, which process a low-resolution image and produce a 2-dimensional vector that represents the overall optical flow of the scene. It is this technology that makes possible optical mice as computer interface devices which track the movement of the surface under the mouse as it is moved.

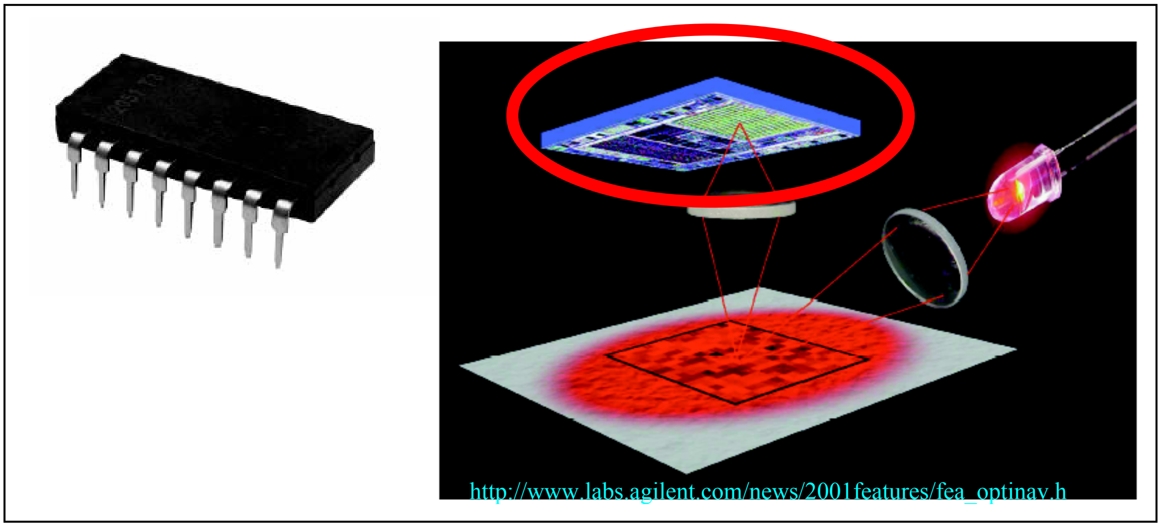


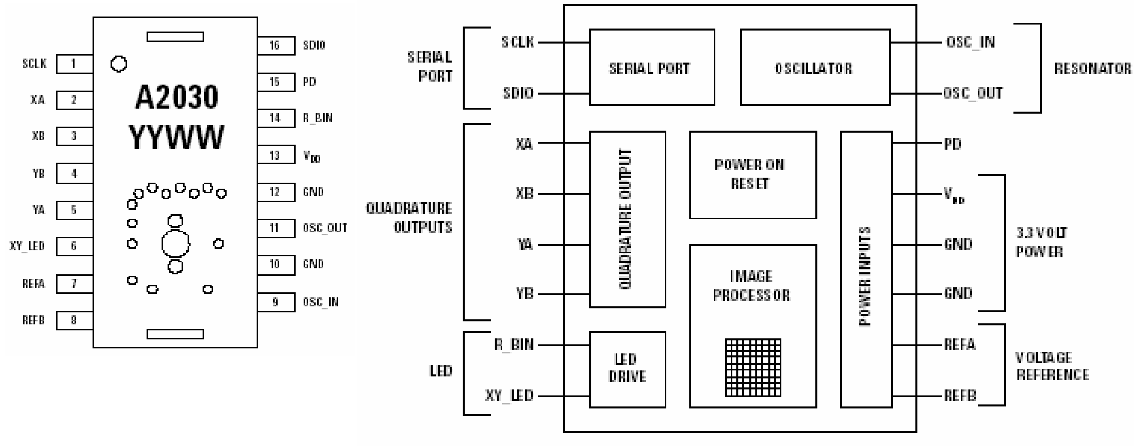
Figure 1:Optical Mouse Chip & Theory of Operation

Each "optical mouse" chip sensor computes optic flow across a low-resolution photosensitive array, in a manner analogous to an element in an insect's compound eye. We propose here a technique whereby these inexpensive optical mouse chips are used to perform optical navigation on miniature robotic platforms.

Figure 2:Compund Eye of the Fly

This approach has the advantages of small size, low power, low cost, redundancy, high speed, parallel processing, and commercial availability of the sensor components. It is particularly suited to implementation on micro scale vehicles on which conventional imagers and panoramic optics are too massive. Specific motivation for this work has come from the development of a miniature robotic flier for Mars exploration. Thus, the following analysis is specifically tailored for a robotic aerial vehicle application, although the technique also has applicability to a rover.

Optical mouse chips offer a number of features important to optical flow measurement for a robotic flier. Each optical mouse chip contains a complete optical navigation system consisting of a 16 x 16 CMOS imager coupled with an image processing engine which compares consecutive frames an determines the 2-dimensional motion of the scene between frames.



from http://literature.agilent.com/litweb/pdf/5988-

Figure 3:Optical Mouse Chip Pinout & Block Diagram

The chips operate at high frame rates of up to 2300 frames per second, which is important for performing robust navigation at high speeds. Each sensor is low power (42mW), low mass (20 g), and inexpensive ($10). In a flier application, terrain following behavior may be achieved using only a single sensor. Complex behaviors such as corridor following can be accomplished with an array of as few as two sensors. More complex navigation can be accomplished by adding additional sensors.

II. Integration Approach

A hierarchical control architecture is recommended in which a number of optical navigation sensors are connected to a single microcontroller which combines the optical flow information from each and determines the motion of the UAV relative to the environment. The local microcontroller communicates to a master microcontroller that combines information from the various sensing subsystems, determines the priority to be assigned to each, and relays control information to affect the locomotion of the aircraft. This hierarchical organization is analogous to the neural structure of the fly and other animals in which the signals from many photoreceptors are combined in Elementary Motion Detectors and Horizontal Systems to produce a unified output that is passed to higher neural functions.

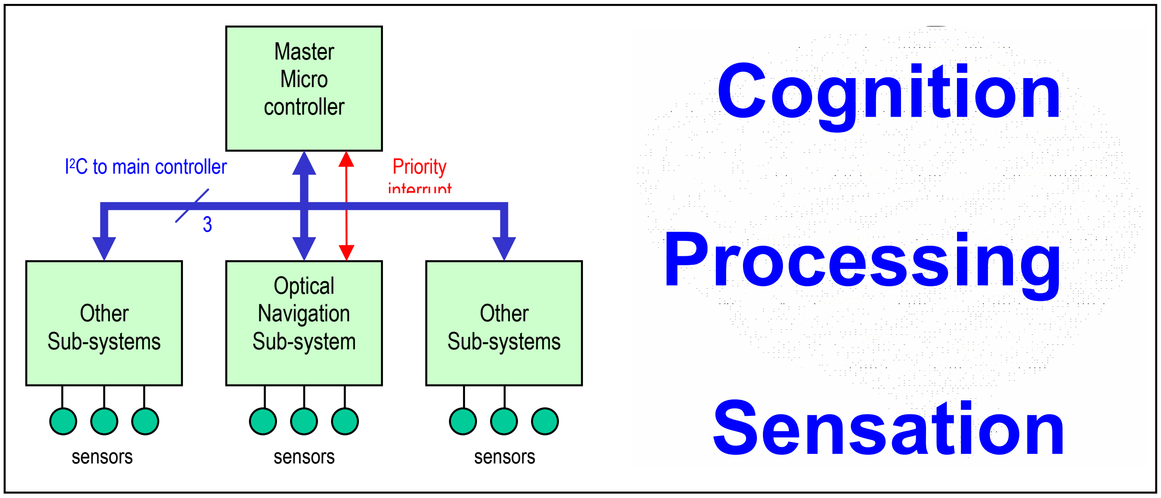


Figure 4: Overall Control Architecture for Sensor Suite

The Inter-Integrated Circuit (I^2C) bus allows the multiple subsystems to be connected using a minimum of wiring and reducing the I/O count on the master microcontroller. It may be advantageous to provide the optical navigation subsystem with a dedicated interrupt line to signal the main microcontroller in case immediate evasive action is required due to a detected obstacle. Alternately, a dedicated communications bus could be provided, as long as there is sufficient I/O on the master micro controller. Usually, however, I/O will be at a premium, as there will be many systems requiring high-level control, including imaging systems, inertial measurement, power, and flight control.

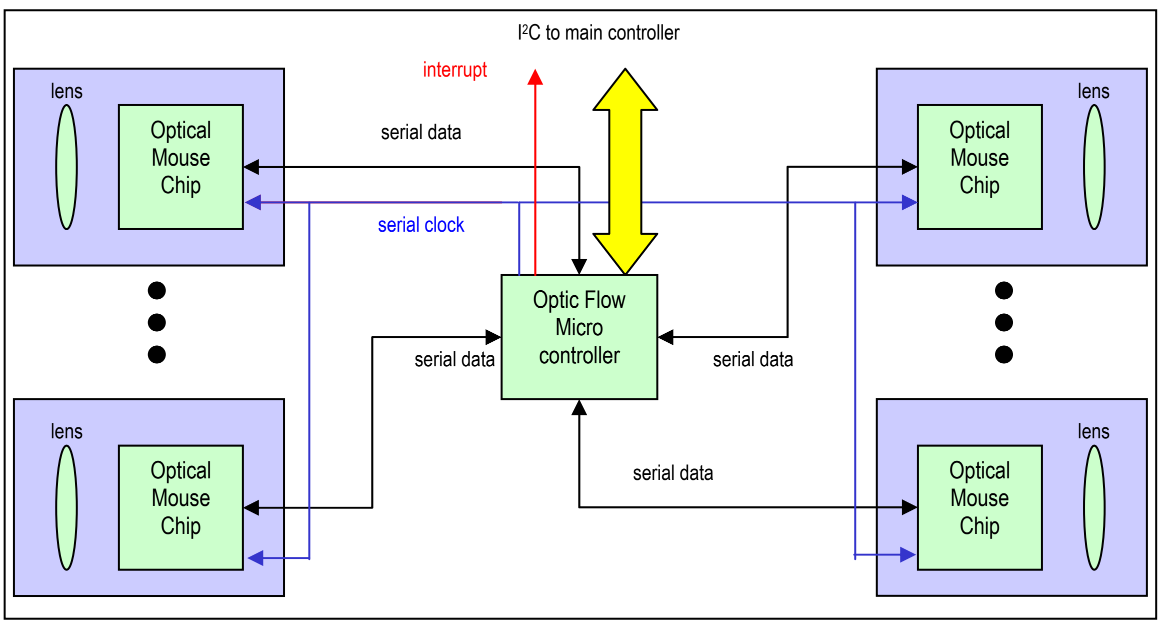


Figure 5: Local Interconnection Between Optical Flow Microcontroller and Sensor Array

Investigation into several candidate microcontroller architectures (PIC, Cygnal, Phillips XA) has revealed that several optical navigation sensors (optical mouse chips) may be easily interfaced to a single microcontroller using a software-driven synchronous serial interface. For applications in which arrays of optical mouse chips are used, the software-

driven approach is preferred to using the dedicated hardware serial port(s) available on the candidate microcontrollers because only one or, at most, two such ports are provided.
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III.The Optical Mouse Integrated Circuit

Agilent manufactures several optical mouse sensor chips: the HDNS-2000 Optical Mouse Sensor, ADNS-2001 Optical Mouse Sensor, ADNS-2051 Low Cost Optical Mouse Sensor, and ADNS-2030 Low Power Optical Mouse Sensor. Although all the parts operate in similar fashion, the HDNS-2000 and ADNS-2001 are slightly older parts that have lower frame rates, less resolution, and fewer adjustable parameters than the newer models. The ADNS-2051 and ADNS-2030 represent the latest additions to the optical mouse chip product line and are virtually identical, with power consumption being the discriminating factor. The low-power device, ADNS-2030, originally targeted for cordless mouse applications, is given special consideration for the following analysis.

A. Characteristics of the Agilent ADNS-2030 Sensor

1. Imager Spatial Resolution

Judging from imagery of USAF test patterns, the pixel spacing is approx. equivalent to 8 line pairs per mm. This equates to around 16 pixels/mm → 62.5um/pixel, and the total active imaging area is 1 mm.

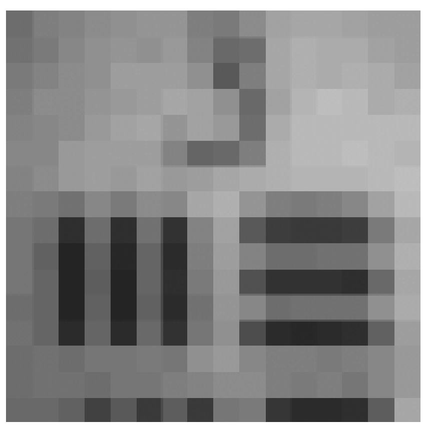


Figure 6: USAF Test Chart Group 3, Element 1, 8 line pairs per mm

Using the counts-per-inch (cpi) rating of the part as a crosscheck, the highest cpi mode is 800cpi, which translates to 31.5 counts per mm. Assuming a two-pixel displacement is required to achieve a count, then, again, the pixel spacing is approximately 63um, and the total active imaging area is 1mm.

Detectable motion is specified as 14 in/s (355 mm/s) at 1500 fps using the stock lens. This equates to 0.24 mm motion between successive frames. The lens-surface distance using the stock lens is 2.4 mm, and the object-to-image distance is 8.8mm. Since magnification is unity using stock lens, we know that there is 4 times the focal length distance between object and image. The focal length of the stock lens is therefore 2.2mm. Thus, the image must not move more than approximately 3 or 4 pixels from frame to frame.

2. Optical Design

One important parameter for selecting the proper lens is the maximum distance the aircraft can move between frames. This is given by the equation

$$distance = \left(\frac{1}{fps}\right) \times velocity,$$

where *velocity* is the ground speed of the aircraft and *fps* is the frame rate of the imager. For the ADNS-2030, the maximum frame rate is 2300 frames per second. It should be noted that the fastest (and thus worst-case) ground speed will be obtained when the aircraft has a tail-wind, and the wind speed adds to the airspeed of the craft. The airspeed of a typical R/C airplane may be estimated using

$$airspeed = C \times P \times RPM,$$

where "C" is a constant (0.00966), "P" is the pitch of the propeller in feet, and RPM is the measured revs of the propeller using any of the popular RPM gauges on the market. This will yield the airspeed in units of miles per hour. Typical R/C airplane airspeeds on earth can be as high as 120 mph, or 53m/s. Mars flight speeds could be in the range of 100m/s. In one frame integration period on Mars, the aircraft could travel 43.5mm, assuming no contribution from wind. The optical mouse chip requires that motion between frames not exceed 4 pixels of motion between frames. For the purposes of this analysis, we will restrict the maximum motion between frames to 2 pixels. Thus, the imager should image an area with width and height 350mm or greater. At 0.0625mm/pixel, this corresponds to a transverse magnification factor of 0.0029 or less. We will assume that the aircraft is designed to follow the terrain 30m above the surface. The focal length f in this arrangement is 87mm (or less). The distance from the lens to the imager focal plane must then be between f and $2f$. Reducing f reduces the longitudinal size of the optical flow sensor at the cost of requiring that larger features be present in the environment, as seen from the equation

$$M_T = -\frac{f}{x_o},$$

where x_o is the distance from the lens to the object being imaged and f is the focal length of the lens. Smaller transverse magnification, or greater minification, means that each pixel maps to a larger object area. The current optical mouse sensor DIP package prevents the lens from being located closer than 2.77mm from the image focal plane. Thus the range of f is between 87mm and 2.77mm.

The specifications for the part state that 80 mW/m^2 at the IC is required for proper operation. The optical design should incorporate optics that are “fast” enough to allow sufficient ambient illumination to support 2300 fps. A “straw man” optical design with focal length f = 25mm will be used in the following analysis. This particular focal length has been chosen, as it is a good compromise between system size and object resolution.

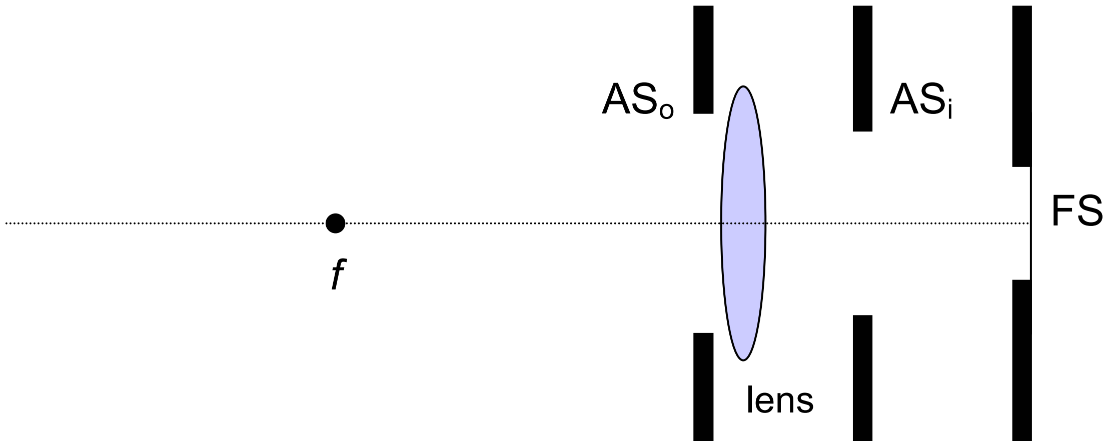


Figure 7: Simple Optical Model Indicating Apertures/Field Stop

- FS = 1.0 mm
- AS_i = 0.8 mm
- f, AS_o are determined by choice of lens
- Distance between AS_i and image focal plane = 2.77mm
- Distance between lens and image focal plane = 25mm (one focal length)

If we momentarily neglect the contribution of AS_o, we find that the entrance pupil, determined by the image of AS_i at the lens position, is 7.22mm in diameter. The f-number for such a system is given by f/# = f / D = 3.46, which is considered reasonably “fast”. The numerical aperture is approximated similarly as NA = D/2f = 0.1444. Numerical aperture is a measure of how much light enters an optical system and is given by NA=sin θ_{max}, where θ_{max} is the half-angle of the largest cone of light that will enter the optical system. For our “straw man” optical design, the full-angle of the cone of light that enters the optical system is 0.29 sterradians (and field of view of around 16 degrees).

From the J.N.Maki paper, *The Color of Mars: Spectrophotometric Measurements at the Pathfinder Landing Site*, the spectral radiance of rock (the dimmest object type) at the Mars Pathfinder site at 600nm is 10 W/ (m^2 sterradian μm). We use the 600nm number because it is closest to the recommended illumination wavelength of 639nm for the optical mouse chip. Multiplying by the full-angle and the wavelength yields 1850mW/m^2, well within the range of 80 mW/m^2 to 25000 mW/m^2 for the optical mouse chip. We could even afford to choose a lens with a clear aperture less than 7.22mm in diameter to further reduce system size.

3. Readout Mechanisms

a) Quadrature Outputs

The ADNS Optical Mouse Sensor provides 4 quadrature signal lines (2 in x, 2in y) that mimic the behavior of differential encoders, as found in mechanical mice. The behavior of these outputs depends on which of two resolution modes is currently active. When the part is placed in 400 counts per inch (cpi) mode, the quadrature outputs report up to 5 states per frame. In 800 cpi mode; the quadrature outputs report up to 10 states per frame. At the reference frame acquisition rate of 1500 frames per second (fps), the time between successive frames is 667μs. Thus the maximum rate at which motion is reported is around 15,000 counts per second. This is a limitation of the quadrature output characteristics – internally, the sensor is able to keep track of many times more motion in each frame. If there is excess motion during a frame period (more motion than can be reported), the sensor outputs the maximum reportable motion during the current frame, and will attempt to report the unreported motion during the next frame period. The quadrature outputs represent the slowest mechanism available in the ADNS 2030 for reading motion during a frame period, and thus is not the mechanism of choice for our optical navigation application. Rather, the serial port will be used to read out the motion as described in the section below.

b) Serial port

The ADNS Optical Mouse Sensor provides a 2-line serial port interface consisting of the following signals:

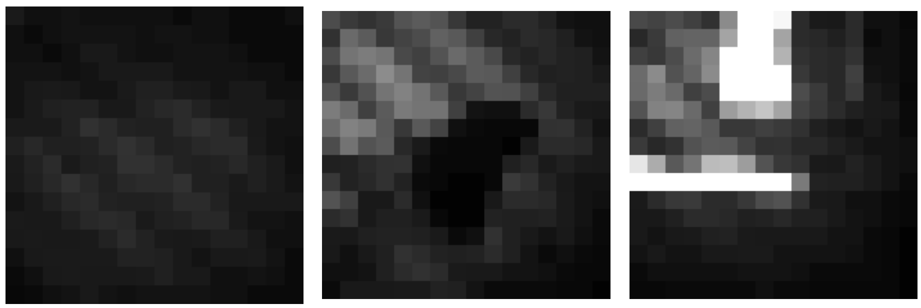
- SCLK – serial interface clock, generated by microcontroller. May not exceed one-quarter of f_{CLK}, the part's master clock frequency, which is fixed at 18 MHz ± 5%. Thus, SCLK may not exceed 4.5MHz.
- SDIO – serial data line, half duplex

Read Operations take 2 Bytes - 1 from microcontroller to Optical Mouse Sensor, 1 the other way. At the minimum clock period of 240ns, each byte takes 1.92μs. The handoff between the microcontroller and the Optical Mouse Sensor requires 100μs, and the reciprocal handoff takes 10ns. The process of reading x/y information requires 3 read operations. Thus, the total time required to read the motion between successive polls using the serial interface is 103.85 μs. This corresponds to a measurement bandwidth of approximately 9.6 kHz. This is 4 times greater than the maximum possible frame rate of the sensor's imager, and thus the slower frame rate will limit the measurement bandwidth.

Although each read operation is capable of conveying displacements of up to 256 counts, the internal buffers can accommodate up to 32 times as much. Making the unrealistic assumption that the chip can detect motion of up to 16 counts each frame (a very conservative upper bound), it will take 16 frames to build up 256 counts. At a frame rate of 2300 fps, the serial line can be read out as slowly as $f_{CLK}/(4*4*16)$ = 70 kbit/sec (sustained) without having residual (unreported) motion. Stated another way, to avoid having unreported motion, the motion should be read every 7 milliseconds or so.

c) Pixel Dump

Pixel data can be obtained via the serial port, but the operation is not particularly fast. In the best-case scenario, a single pixel value is available each frame. Thus, it takes 256 frames to read out the entire image area. At 2300 fps image acquisition, this is less than 10 fps readout. Also, since each pixel is acquired during a different frame, motion must be negligible over the 256-frame period. This mode is useful for optical alignment diagnostics. There is little motivation to use pixel dump mode in a navigation application because the optical mouse chip has the means of determining motion between successive frames on-chip.



Pixel dumps from the ADNS through "card camera" optics

4. Power Considerations

The low-power optical mouse chip ADNS-2030 draws no more than 23mA (76mW) when measurements are being taken, not counting the power draw from sensor to microprocessor communications. In power-saving inactive mode, the chip draws no more than 30µA (0.099mW). For each group of sensors, the power required by the local microcontroller must be included as power "overhead". For most small microcontrollers, this will be on the order of 50mW. The inactive mode allows power to be conserved at times when the optical mouse sensor inputs are not required (i.e. when vehicle is at an altitude/configuration when other sensors are adequate).

5. Temperature Operating Range

The recommended temperature range for the chip is from 0 to 40 deg C. Testing over a wider range will be required in preparation for a Mars mission.

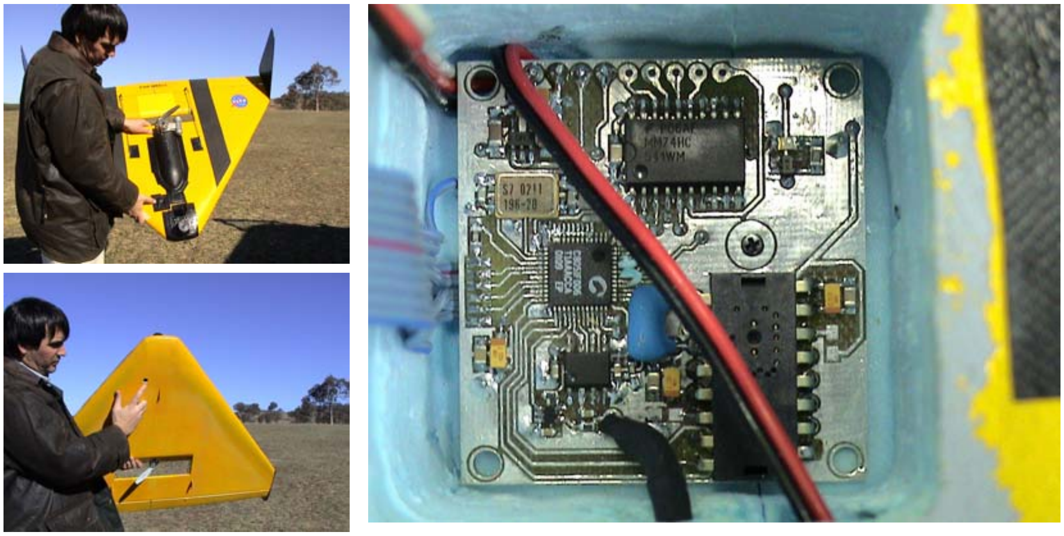
IV. Prototype Testing on Unmanned Aerial Vehicle

A prototype optical navigation sensor for aerial robotic applications has been constructed at the Australian National University using ADNS-2051 parts recovered from Logitech Dual-Optical mice and tested aboard a delta-wing micro unmanned aerial vehicle (UAV) being developed for future Mars exploration. The ADNS-2051 optical mouse chip is virtually identical to the ADNS-2031, but has higher power consumption. Its availability in duplicate in the Dual-Optical Mouse product was motivation for its use in the proof-of-concept sensor. Unlike more primitive models such as the HDNS2001, the ADNS-2051 and ADNS-2031 have many variables that can be "tweaked" to operate with different surface, and also contain a digital interface that allows image capture from the 16x16 array, and digital read-out of movement computations.

Fig 8: A 5 Kg BEES flyer with Bioinspired sensors embedded in the nose area including the mouse chip adapted optic flow sensor looking downwards on the left in the nose area

A. Prototype Implementation

ADNS2051 chips were removed from an optical mouse, and built into a circuit that follows the Agilent reference design. On the circuit is a Cygnal 8051 type microcontroller to configure, read from, and telemeter the data from the chip. The microcontroller is in-circuit-programmable, and also allows a debugging mode to enable the image to be downloaded through the serial port for adjusting focus and checking frame rate. The implementation was deliberately made low density with additional connectors and lines to allow ongoing development and multiple implementation options. Mass was less than 15g less optics.



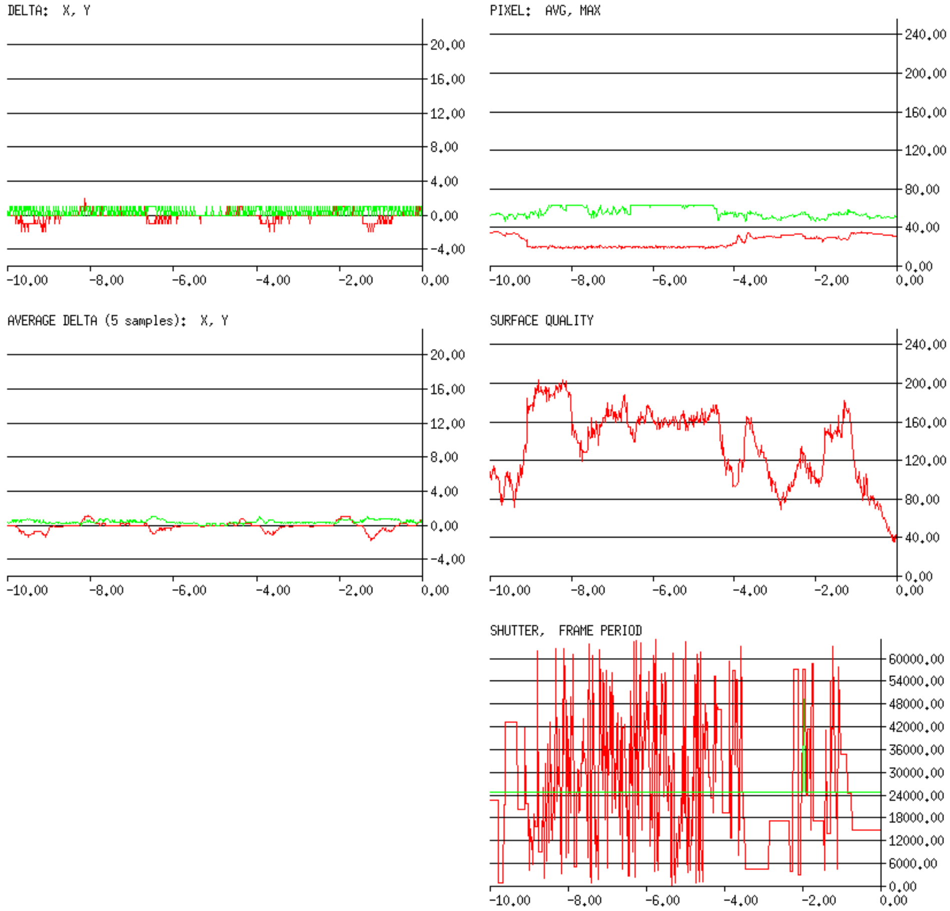
Top left, port in the wing where the instrument is installed. Bottom left underside of wing showing where the optics looks though the wing. Right the circuit embedded in the wing, major components from top left clockwise crystal (silver), buffer for servo motor drive (inline package), ADNS 2051 (large staggered dip), Cygnal 8051 microcontroller.

New optics were required for the device, since the standard Agilent optics is designed for very close focusing. The optics placed over the imaging element were adapted from a CMOS card camera module intended for surveillance. The field of view of the chip was 40^0 when using a 3.7mm focal length lens.

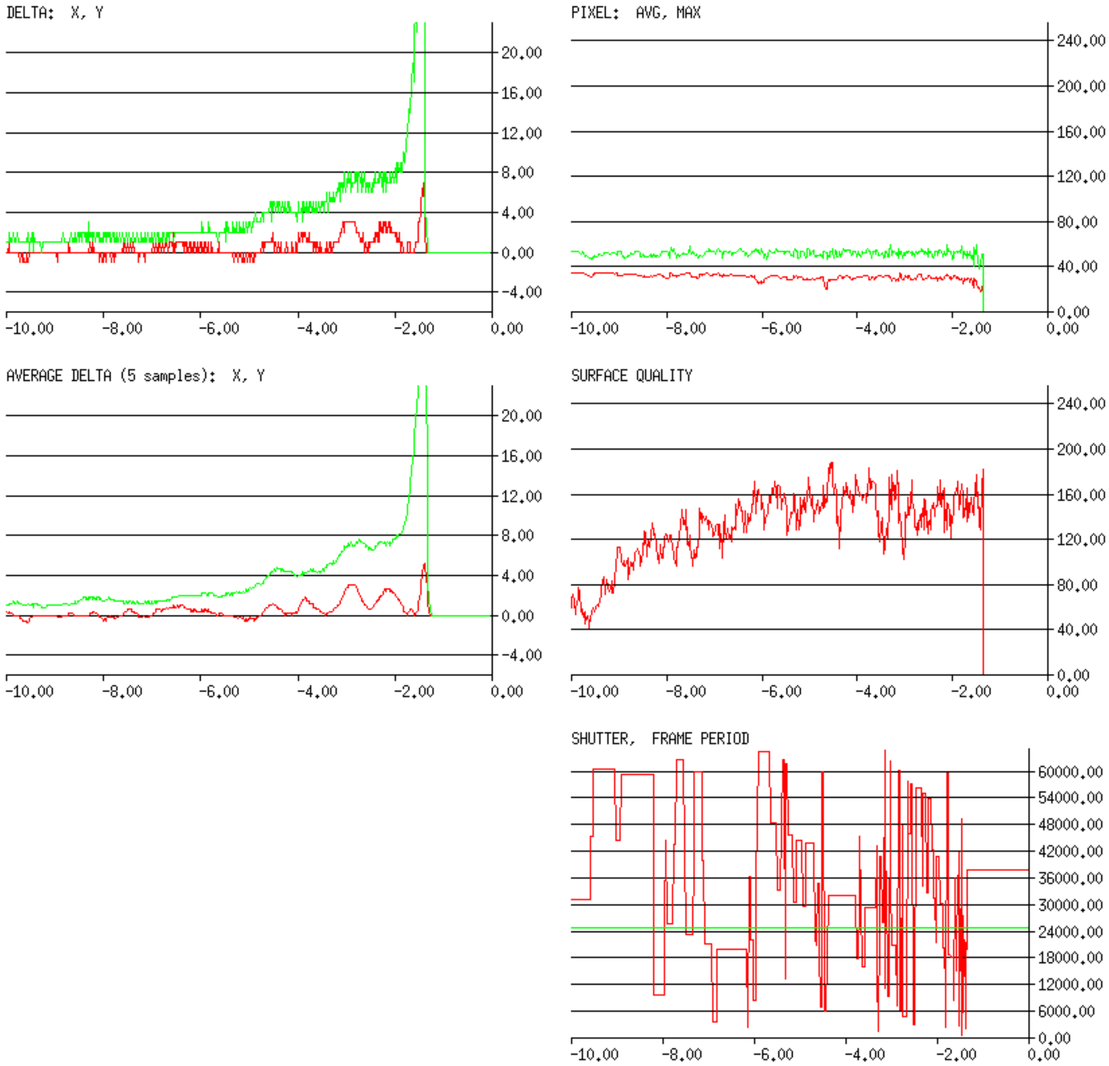
The implementation includes an I2C interface and can drive 4 servomotors and decode 1 servo stream. Removal of all other functions apart from I2C and JTAG programming would reduce the package to ½ of its current linear dimensions. A smaller CPU could be used also, that would fit inside the shroud for the optics on the other side of the board.

B. Test Flight

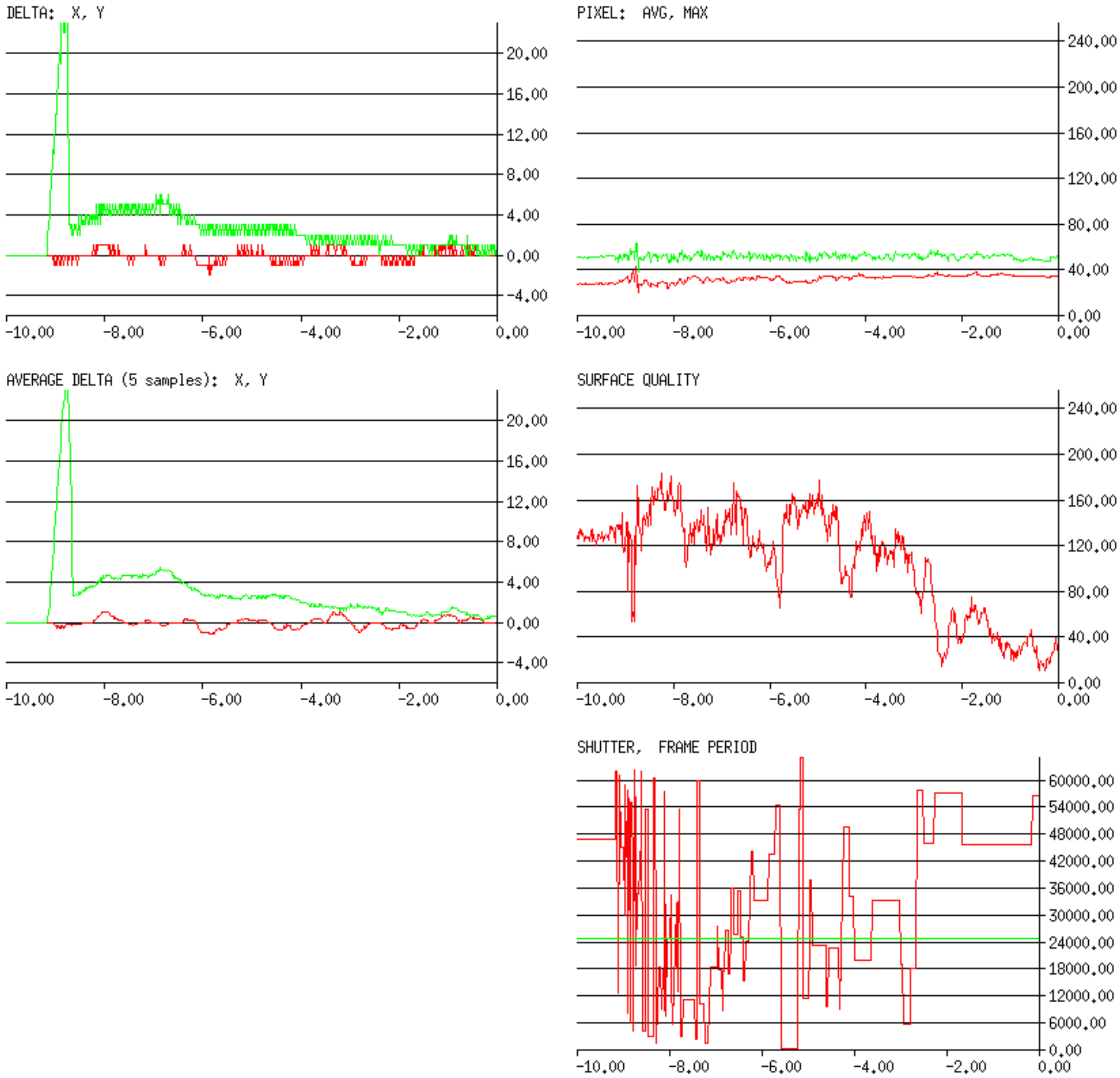
The device was mounted on a Type 2 (5kg) aircraft with the lens looking through a hole in the wing. The measurements were telemetered to the ground for logging. Large motions could only be seen when the pilot performed low speed aborted landings at 1-2m height, or extremely high speed flights at 4-6m. Typical motion at cruising speed and safe altitude was of the order of 0.5 of output quanta.



Normal flight with the mouse chip looking down, the measured rates are low, at less than one quanta. Delta X and Y are the motion signals. Quality of the surface (texture) consistently adequate (middle right). Averaging helps increase the signal resolution, at the obvious cost of temporal response (top right).



Landing flight. Rates are measurable, and consistent with the landing experience. Rapid increase in rate is apparent at the end of the flight.



Launch, rapid acceleration, followed by climb out.

C. Findings

The chip is designed to measure very rapid image motion, which impacted the magnitude of the output signal. The low resolution of the imaging plane means that very high rates of motion are required in order to achieve even a single quanta output. The field of view produced by the optics we added was, as expected, too wide at 40^0. Based on the logged data, a field of view of 5^0 to 10^0 will be more appropriate for terrestrial UAV flight. The concern with reducing field of view are mainly light capture, and secondly outages in contrast in the image. The former will simply limit the conditions under which flight is permissible, the latter will depend on the environment and will set limits to the aggressiveness of terrain following.

D. Future Plans

We will modify the optics and onboard software to improve sensitivity. Loops can then be easily closed and embedded on the craft after reliable and strong motion signals are attained.

E. Conclusion

Preliminary flight tests have validated the use of the ADNS Optical Mouse Chip for terrain following behavior on a robotic flier. The ADNS-based sensor combines the advantages of low power, low mass, and low volume, enabling more advanced navigation on micro scale robotic vehicles than otherwise possible.

F. Implementation Stages

ADNS2051 chips were removed from an optical mouse, and built into a circuit that follows the Agilent reference design. On the circuit is a Cygnal 8051 type microcontroller to configure, read from, and telemeter the data from the chip. The microcontroller is in-circuit-programmable, and also allows a debugging mode to enable the image to be downloaded through the serial port for adjusting focus and checking frame rate. The implementation was deliberately made low density with additional connectors and lines to allow ongoing development and multiple implementation options. Mass was 15g less optics.

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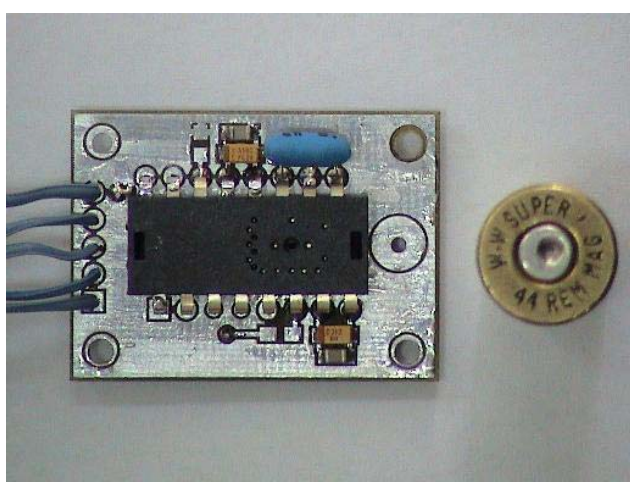
The implementation includes an I^2C interface and can drive 4 servomotors and decode 1 servo stream. Removal of all other functions apart from I^2C and JTAG programming would reduce the package to ½ of its current linear dimensions. A smaller CPU could be used also, that would fit inside the shroud for the optics on the other side of the board.



a) Test Flight

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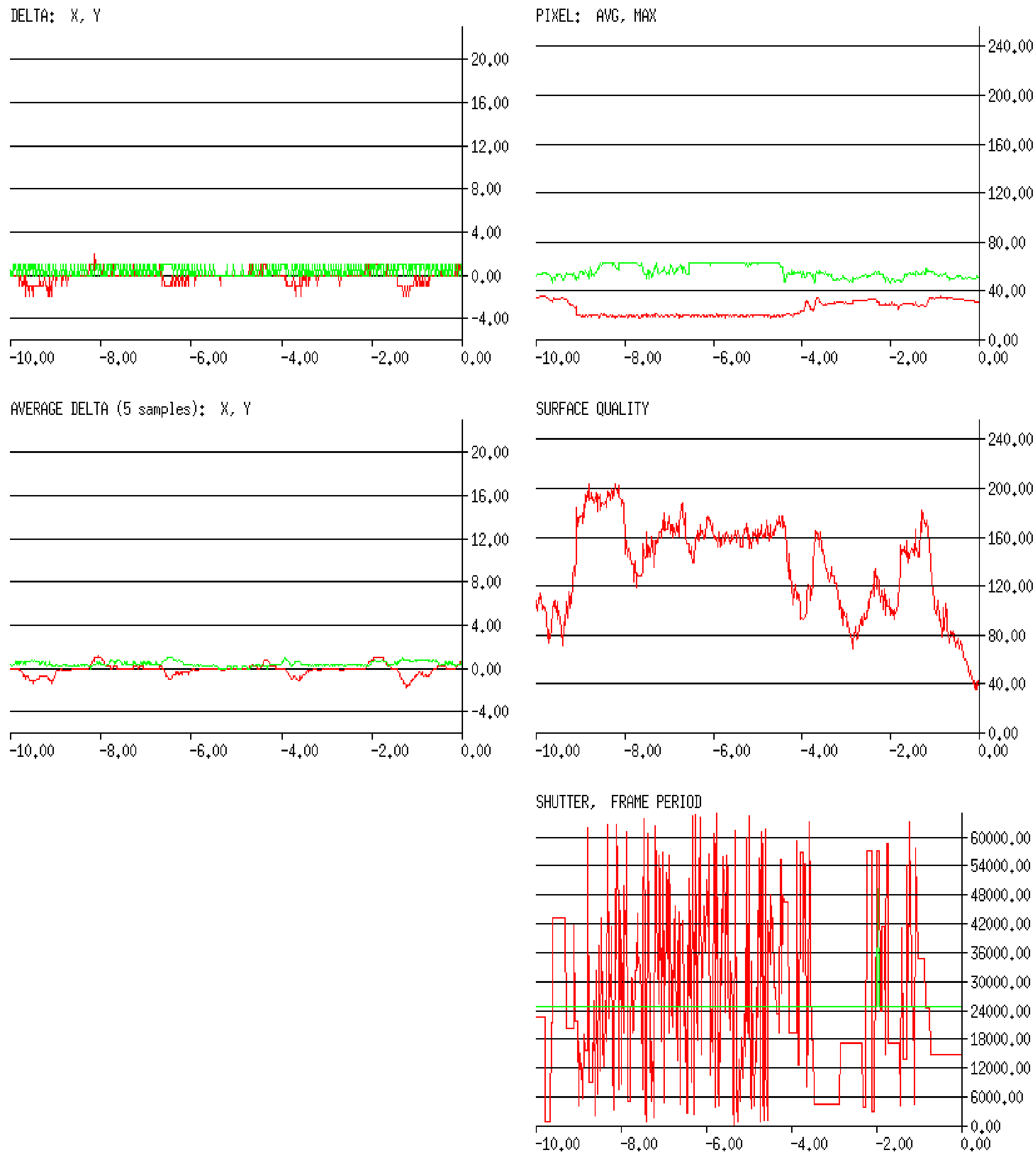


First prototype of the mouse chip. Normal flight with the mouse chip looking down, the measured rates are low, at less than one quanta. Delta X and Y are the motion signals. Quality of the surface (texture) consistently adequate (middle right). Averaging helps increase the signal resolution, at the obvious cost of temporal response (top right).

2. Second Implementation

The first implementation of the embedded optical flow device was a general purpose device, designed to test the concept. A refined implementation was developed at the same time, which could be accessed by any computer with 3 digital I/O pins. This device was more compact and is currently in service, although it is worth stating that it was superseded by newer developments. The ADNS2051 is essentially a stand-alone device, with (unfortunately) a proprietary serial bus interface. This design is cabled to communicate with the modular avionics suite.

Tests have revealed that the sensor is extremely reliable over natural terrain when light levels are high. Late afternoon operation is impossible, and indoor operation is marginal at best. Consequences of low sensitivity include lens size defining the size of the device. Although the chip is rather large, it is still dominated by the lens and housing.

Another difficulty with the current implementation is that only two devices can be driven at once using the flight computer – and in so doing, the function of the flight computer is compromised somewhat.

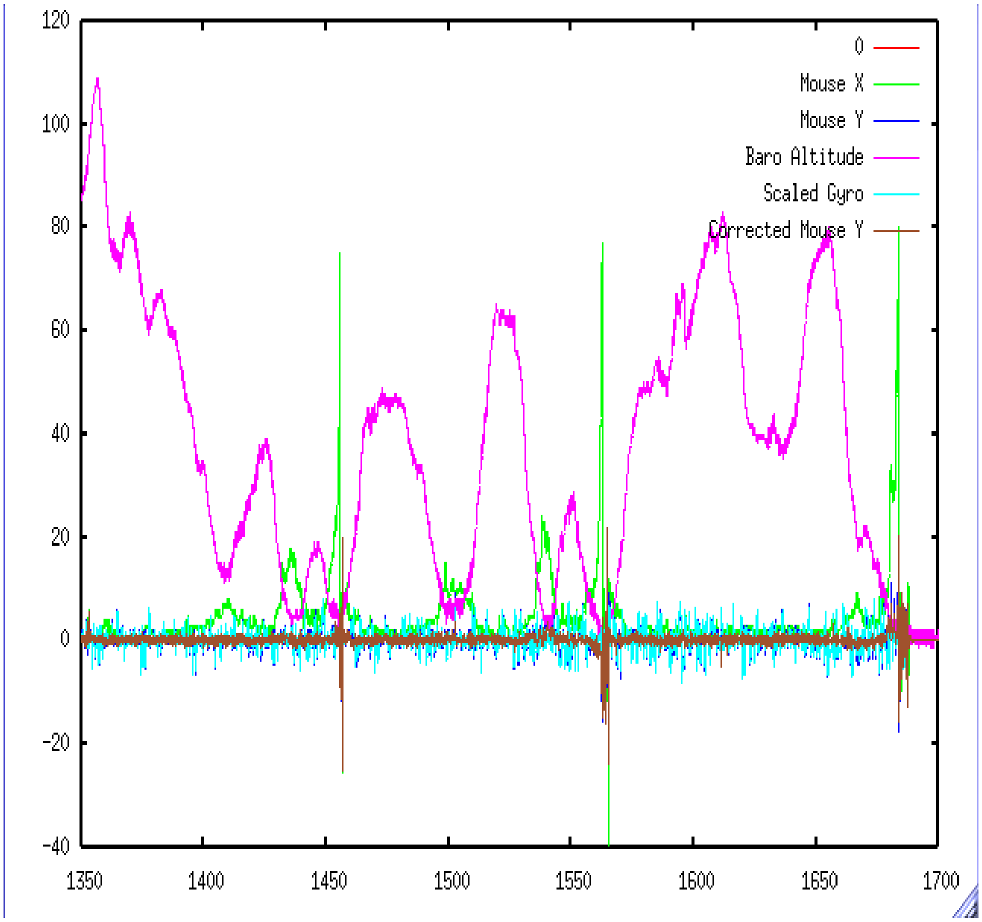
ADNS-2051 chips are difficult to source, with long (unbounded) lead times, and large minimum order quantities. Scavenging from optical mice has become ineffective, due to similarly packaged variants that do not have a serial interface.

3. Third Implementation

The implementation currently planned for the 2004 test, is based on the ADNS-2620, a smaller, higher performance, and de-optioned variant of the 2051. This unit is literally half the size, and half the power consumption. Some of the features of the original have been dropped, including continuously variable frame rate, and system reset. The issue of optics becomes even more important with this unit due to its small footprint.

Lead-time on 120 units was 15 weeks when they were ordered in Jan 2004.

The final implementation consists of a microcontroller controlling up to 8 units, with I^2C and RS-232 interfaces. To complement the small chip size, small connectors will be employed. Each of the chips will be mounted on its own board, although boards containing multiple chips would be possible with minimal effort. Optics will be continue to be of the type used in security cameras, however options must be sought on this front to reduce size. Housings for the optics will be custom machined, since there is no appropriate commercial option in the size range.



Second revision of the optical flow sensor. The larger focal length, and additional instrumentation show the detail of the optical flow response to aircraft movement. At low barometric altitude, the flow signal is strong, at high altitude the flow signal is weak. The absence of glitches and drop outs is positive. Note that the optical flow sometimes reverses at low altitude due to aliasing. The frame rate has subsequently been programmed to be faster to overcome this although low light performance will suffer.